IMPLEMENTATION OF POWER ELECTRONIC TRANSFORMER USING PI AND FUZZY LOGIC CONTROLLERS

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Abstract— This paper presents a novel topology of power electronic transformer. In the design process, the AC/DC, DC/AC, AC/AC converters and high frequency transformer have been used. One matrix converter operates as AC/AC converter in power electronic transformer. The proposed power electronic transformer performs typical functions and has advantages such as power factor correction, voltage sag and swell elimination, voltage flicker reduction and protection capability in fault situations. Power quality improvement with proposed power electronic transformer using PI and fuzzy logic controllers has been verified by the simulation results.

Keywords-Power quality; Voltage sag and swell; Power electronic transformer; AC/AC converter

I. INTRODUCTION

Transformers are widely used in electric power system to perform the primary functions, such as voltage transformation and isolation. Transformers are one of the heaviest and most expensive devices in an electrical system because of the large iron cores and heavy copper windings in the composition [1]. A new type of transformers based on Power Electronics (PET) has been introduced, which realizes voltage transformation, galvanic isolation, and power quality improvements in a single device. The PET provides a fundamentally different and more complete approach in transformer design by using power electronics on the primary and secondary sides of the transformer. Several features such as instantaneous voltage regulation, voltage sag compensation and power factor correction can be combined into PET.

Different topologies have been presented for realizing the PET, in recent years [2]-[7]. In [2] the AC/AC buck converter has been proposed to transform the voltage level directly and without any isolation transformer. This method would cause the semiconductor devices to carry very high stress.

In second type, the line side AC waveform is modulated into a High or medium Frequency (HF or MF) square wave, coupled to the secondary of HF (MF) transformer, and again is demodulated to AC form by a converter in second side of HF (MF) transformer. This method however does not provide any benefits such as instantaneous voltage regulation and voltage sag compensation due to lack of energy storage system. In second type matrix converter is a direct AC-AC power converter employing bidirectional switches. In addition to the basic ability of power converter providing a sinusoidal variable voltage variable frequency to the load, matrix converter has many attractive features: no bulky DC-link capacitor, ability to make sinusoidal input current, high efficiency, compact circuit design and regeneration capability [3]-[5].

Another type is a three-part design that utilizes an input stage, an isolation stage, and an output stage [6]-[10]. These types enhance the flexibility and functionality of the electronic transformers owing to the available DC links. This approach can perform different power quality functions and provide galvanic isolation but they need whether too many power electronic converters and DC-link electrolytic capacitors.

Custom power devices are introduced in the distribution system to deal with various power quality problems faced by industrial and commercial customers due to increase in sensitive loads such as computer and adjustable speed drives and use of programmable logic control in the industrial process [11], [12].

This paper investigates the PET that includes three parts: input stage, an isolation stage, and an output stage. Proposed PET includes AC/AC matrix converter. The proposed AC/AC converter can generate desired output voltage from square input voltage. The main point of proposed PET is reduction of the stage and components of the three-part PETs. The reliability and power quality of distribution system can be significantly improved by using proposed PET. To verify the performance of the proposed PET, computer -aided simulations are carried out using MATLAB/SIMULINK.

II. CONVENTIONAL PETS

Fig. 1 shows the basic block diagram of the PET using HF (MF) AC-link without DC-link capacitor. In this system, the line side AC waveform is modulated with a converter to a high-frequency square -wave and passed through a HF (MF) transformer and again with a converter, it is demodulated to AC form power-frequency. Since the transformer size is inversely proportional to the frequency, the HF (MF) transformer will be much smaller than the power-frequency transformer. So, the transformer size, weight and stress factor is reduced considerably [3].

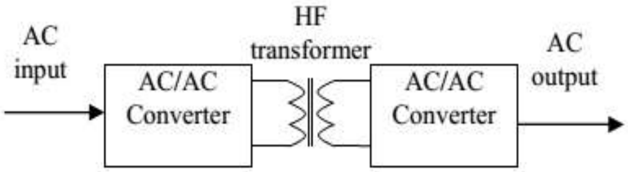


Figure1.Block Diagram of electronic transformer using HF (MF)using AC link

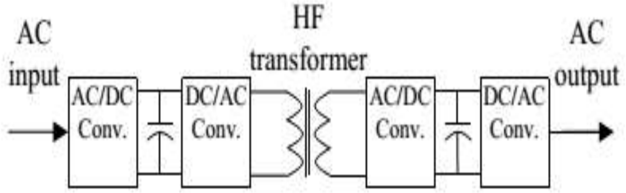


Figure2.Block Diagram of Power Electronic based Transformer (PET) with DC link.

This converter does not provide any benefits in terms of protecting the critical loads from the instantaneous power interruptions due to lack of energy storage system [7].

Fig. 2 shows the basic block diagram of a PET with DC-link capacitor which includes three stages. First stage is an AC/DC converter which is utilized to shape the input current, to correct the input power factor, and to regulate the voltage of primary DC bus. Second stage is an isolation stage which provides the galvanic isolation between the primary and secondary side. In the isolation stage, the DC voltage is converted to a high-frequency square wave voltage, coupled to the secondary of the HF (MF) transformer and is rectified to form the DC link voltage. The output stage is a voltage source inverter which produces the desired AC waveforms [4]-[10].

In comparison to first PET, the voltage or current of PET can be flexibly controlled in either side of HF (MF) transformer. It is possible to add energy storage to enhance the ride-through capability of the PET or to prepare integrated interface for distributed resources due to the available DC links. It prevents the voltage or current harmonics to propagate in either side of the transformer, even if the input voltage has low order harmonic content or the load is not linear but they need too many converters (AC/DC or DC/AC) and DC-link electrolytic capacitors. Thus they are resulted in a rather cumbersome solution and multiple power conversion stages can lower the transformer efficiency.

III PROPOSED PET

The block diagram of the proposed PET is shown in Fig. 3. As can be seen from the Fig. 3, this is a three-stage design that includes an input stage, an isolation stage and an output stage. In the input stage, there is a converter, which converts the input AC voltage to DC voltage. The second part of the converter is formed by a DC/AC converter. This part of the converter contains the MF transformer with the high insulation capability. In the output part, the high frequency voltage is revealed as a power-frequency voltage. In this paper, a three-part design is introduced. It is a new configuration based on the matrix converter with new function shown in Fig. 3. It can provide desired output voltage. In addition, it performs power quality functions, such as sag correction, reactive power compensation and is capable to provide three-phase power from a single phase system. The PET has three stages and each stage can be controlled independently from the other one. Many advantages of the PET such as output power quality and power factor correction depend on appropriate close-loop control, and correlative research is necessary. The reliability of a system is indirectly proportional to the number of its components. The main purpose of proposed PET is reduction of the power delivery stage (AC/DC and DC/AC links) in PET with DC-link.

The input stage is a three or single phase PWM rectifier, which is used to convert the primary low frequency voltage into the DC voltage. The main functions associated with the rectifier control are shaping the input current, controlling the input power factor, and keeping the DC-link voltage at the desired reference value. Many control methods are presented for control of input stage in conventional PET, which could be used in proposed PET. Fig. 4 shows three phase rectifier with input inductances. A three phase PWM rectifier is used in this paper, which operates same as input stage of conventional PET [8]-[10]. Fig. 5 shows input stage control diagram. To realize constant DC voltage and keep input current sinusoidal, the double control loops, a DC voltage outer loop and an AC current inner loop, are adopted. For most description refer to [8]-[10]. As can be seen from Fig. 5, the reference for the active current is derived from the DC voltage outer loop. The reference for the reactive current is set to zero to get unity power factor. The current error signals are input the current regulators and then form the modulation signals. If the *d* axis of the reference frame is aligned to the grid voltage, we obtain $V_{inq} = 0$.

Isolation stage is contained a single-phase high frequency voltage source converter (VSC), which converts the input DC voltage to AC square voltage with high (or medium) frequency and HF (MF) transformer. The main functions of the HF (MF) transformer are such as: voltage transformation and isolation between source and load.

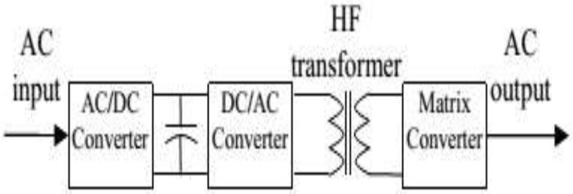


Figure3

Block diagram of proposed PET with DC link

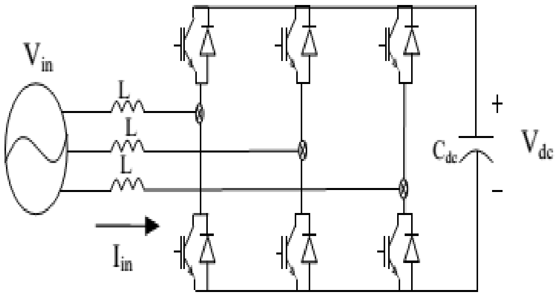


Figure4. Structure of the proposed input stage

Structure of the proposed isolation stage is shown in Fig. 6. Circuit diagram of VSC is the same as H-bridge cell. To simplify the design of the control system, open loop control is applied for the VSC. The principle of modulation is based on a comparison of a sinusoidal reference waveform with zero carrier waveform.The principle of switching H-bridge is described with conditions below:

Condition 1: if sin wave ≥ 0, then H_1 and H_2 are turned on.

Condition 2: if sin wave < 0, then H_3 and H_4 are turned on.

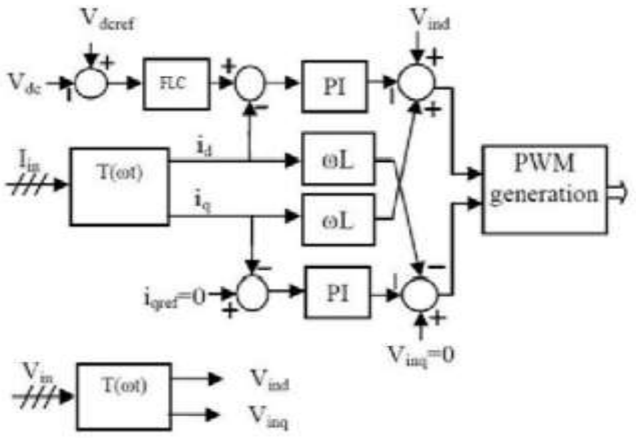


Figure 5. Input stage control diagram.

If sine reference wave has a frequency f_r and an amplitude A_r then output voltage of VSC has a frequency f_r. By neglecting the losses of HF (MF) transformer, the HF (MF) transformer can be treated as a proportional amplifier. V_i, V_s are the primary and secondary voltage in HF (MF) transformer, respectively and N points to turn ratio. A square voltage source can be generated by isolation stage. Fig. 7 shows a matrix converter with novel function for square to sinusoidal voltage converter. Matrix converter topology employs six bidirectional switches to convert high frequency single-phase input directly to a power frequency (50/60 Hz) three- phase output.

The proposed converter generates desired output voltage with suitable shape and frequency. Operation of proposed converter is the same as three levels voltage source inverter but here voltage source has two polarities. Several modulation strategies have been proposed for traditional inverters. Among these methods, the most common used is the pulse widths modulation (PWM). The principle of the PWM is based on a comparison of a sinusoidal reference waveform, with triangular carrier waveform. At each instant, the result of the comparison is decoded in order to generate the correct switching function corresponding to a given output voltage level. In proposed PET, PWM modulation technique applied to a matrix converter is employed. The main point of switching is this point that with changing of polarity in input sources on switches are turned off and other switches in arms are turned on.

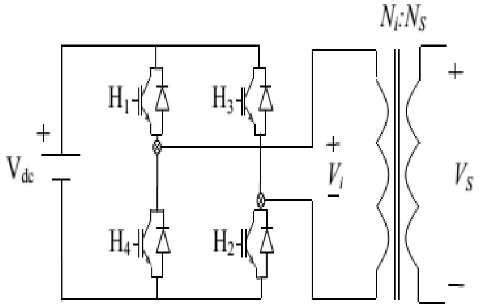


Figure6.Structure of the proposed isolation stage.

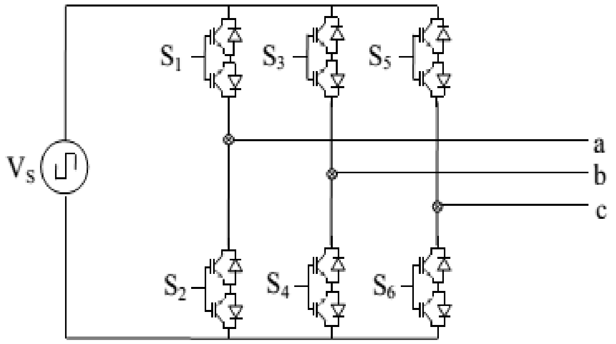


Figure 7.Proposed matrix converter

In this method, there are two important parameters to define: the amplitude modulation ratio, or modulation index m, and the frequency modulation ratio p. $V_{ref\ max}$ and $V_{carrier\ max}$ are the amplitudes of reference voltage and carrier voltage, respectively. On the other hand, f_S is the frequency of the main supply and f_T the frequency of the triangular carrier.

As it can be seen in Fig. 8, the matrix converter is controlled by PWM method. In this case, the direct axis, quadratic axis, and zero sequence quantities for three-phase sinusoidal signal is computed by Park transformation. Then the dq voltage terms are compared by reference signals V_{dref} and V_{qref} and error signals enter to PI controllers. Next the PI controller outputs are transformed to three-phase sinusoidal abc voltage terms and used to generate appropriate matrix gate pulses.

IV FUZZY LOGIC AND PI CONTROLLERS

It is necessary to establish a meaningful system for representing the linguistic variables in the matrix. For this example, the following will be used:

"N" = "negative" error or error-dot input level
"Z" = "zero" error or error-dot input level
"P" = "positive" error or error-dot input level
"H" = "Heat" output response
"-" = "No Change" to current output
"C" = "Cool" output response

Define the minimum number of possible input product combinations and corresponding output response conclusions using these terms. For a three-by-three matrix with heating and cooling output responses, all nine rules will need to be defined. The conclusions to the rules with the linguistic variables associated with the output response for each rule are transferred to the matrix.

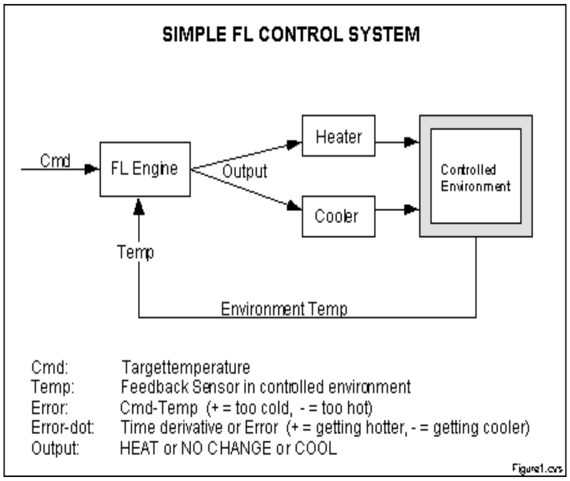


Figure 8 A simple block diagram of the control system

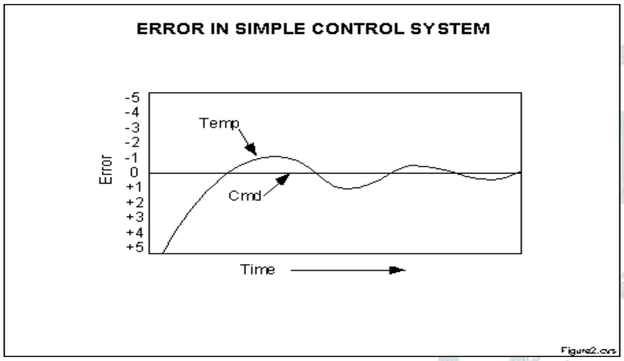


Figure 9 - Typical control system response

It shows what command and error look like in a typical control system relative to the command set point as the system hunts for stability. Definitions are also shown for this example.

DEFINITIONS:

INPUT#1: ("Error", positive (P), zero (Z), negative (N))

INPUT#2: ("Error-dot", positive (P), zero (Z), negative (N))

CONCLUSION: ("Output", Heat (H), No Change (-), Cool (C))

INPUT#1 System Status

Error = Command-Feedback

P=Too cold, Z=Just right, N=Too hot

INPUT#2 System Status

Error-dot = d(Error)/dt

P=Getting hotter Z=Not changing N=Getting colder

OUTPUT Conclusion & System Response

Output H = Call for heating - = Don't change anything C = Call for cooling

Linguistic rules describing the control system consist of two parts; an antecedent block (between the IF and THEN) and a consequent block (following THEN). Depending on the system, it may not be necessary to evaluate every possible input combination (for 5-by-5 & up matrices) since some may rarely or never occur. By making this type of evaluation, usually done by an experienced operator, fewer rules can be evaluated, thus simplifying the processing logic and perhaps even improving the FL system performance.

. There are different membership functions associated with each input and output response. Some features to note are:

SHAPE - triangular is common, but bell, trapezoidal, haversine and, exponential have been used. More complex functions are possible but require greater computing overhead to implement.. HEIGHT or magnitude (usually normalized to 1) WIDTH (of the base of function), SHOULDERING (locks height at maximum if an outer function. Shouldered functions evaluate as 1.0 past their center) CENTER points (center of the member function shape) OVERLAP (N&Z, Z&P, typically about 50% of width but can be less).

Table 5.1 Fuzzy control rules

E/CE	**LN**	**MN**	**SN**	**ZE**	**SP**	**MP**	**LP**
LN	**LP**	**LP**	**LP**	**MP**	**MP**	**SP**	**ZE**
MN	**LP**	**MP**	**MP**	**MP**	**SP**	**ZE**	**SN**
SN	**LP**	**MP**	**SP**	**SP**	**ZE**	**SN**	**MN**
ZE	**MP**	**MP**	**SP**	**ZE**	**SN**	**MN**	**MN**
SP	**MP**	**SP**	**ZE**	**SN**	**SN**	**MN**	**LN**
MP	**SP**	**ZE**	**SN**	**MN**	**MN**	**MN**	**LN**
LP	**ZE**	**SN**	**MN**	**MN**	**LN**	**LN**	**LN**

ZE- Zero, LN-Large Negative, SN-Small Negative,
MN-Medium Negative, LP-Large Positive
MP-Medium Positive, SP- Small Positive

V MATRIX CONVERTER

The main advantage of matrix converter is elimination of dc link filter. Zero switching loss devices can transfer input power to output power without any power loss. But practically it does not exist. The switching frequency of the device decides the THD of the converter. Maximum power transfer to the load is decided by nature of the control algorithm. Matrix converter has a maximum input output voltage transfer ratio limited to 87 % for sinusoidal input and output waveforms, which can be improved. Further, matrix converter requires more semiconductor devices than a conventional AC-AC indirect power frequency converter. Since monolithic bi-directional switches are available they are used for switching purpose.

Three phase matrix converter consists of nine bidirectional switches. It has been arranged into three groups of three switches. Each group is connected to each phase of the output. These arrangements of switches can connect any input phase. In the Figure 6.7 filled circle shows a closed switch. These 3X3 arrangements can have 512 switching states. Among them only 27 switching states are permitted to operate this converter. For safe operation, it should follow the given rules.

1. Do not connect two different input lines to the same output line (input short circuited)

2. Do not disconnect the output line circuits (output open circuited)

Figures 10 to 12 are showing different operating states of matrix converter. Here A, B and C are input phase voltage connected to the output phase. Figure 10 shows synchronous operating state vectors of three matrix converter. It shows that the converter switches are switched on rotational basis. In this case no two switches in a leg are switched on simultaneously. These states will not generate gate pulse when one phase of the supply is switched off.

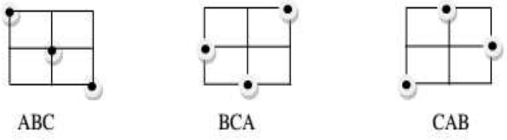


Figure10. Matrix Converter Rotating Vectors (Synchronous Vectors)

Figure11 shows inverse operating state vectors of three matrix converters. In this any one phase is rotated in such a way that it connects all the output phase in a cycle of operation. This operation may be selected during reverse operation of induction motor.

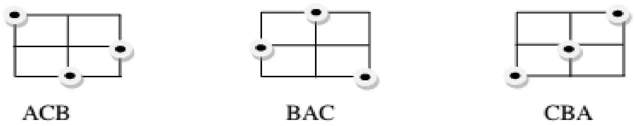


Figure11. Matrix Converter Rotating Vectors (Inverse Operation)

Figure11 shows zero vector of the matrix converter. Here all the output phases are connected in a single input line. It leads to damage to the device. Because three phase loads are directly connected to the single phase line.

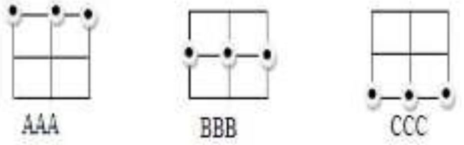


Fig11 Matrix Converter Zero Vectors

Figure12 shows active vectors of the matrix converter which are the operating states in direct conversion. There are 18 operating states are available. We can select any combination for the operation of matrix converter.

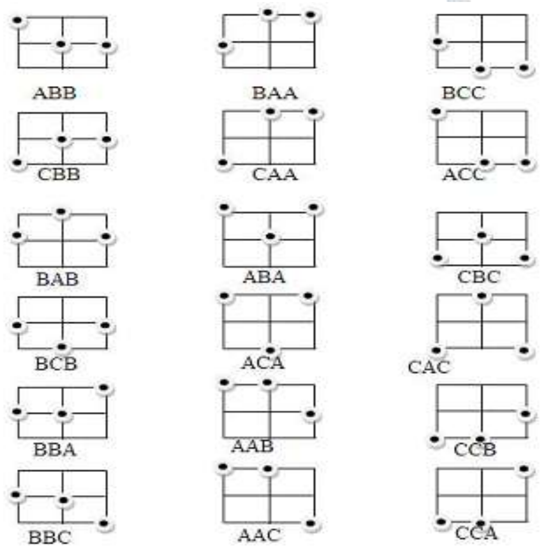


Figure12 Matrix Converter Active Vectors (Pulsating)

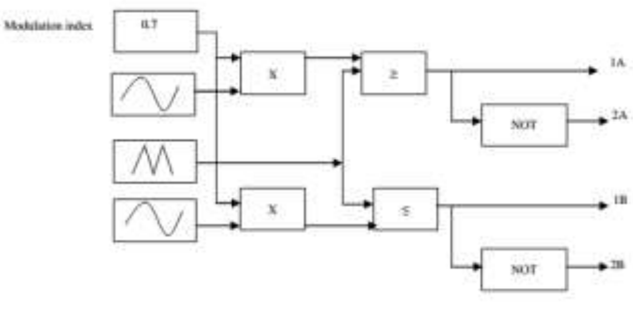


Figure13 Generation of sinusoidal pulse width modulation gate pulse

Figure13 represents development of sinusoidal pulse width modulation gate signal using Matlab logic blocks. Sinusoidal pulse width modulation gate pulse can be generated using triangular signal. Triangular signal and sinusoidal reference signal are compared to get the sinusoidal pulse width modulation gate pulse. The frequency of the sinusoidal function is fixed. Variable pulse width of the gate pulse can be obtained by using triangular signal of varying time period. Modulation index gives the information about „ON‟ time of the gate pulse. It is calculated as switch on time divided by switch ON time plus OFF time of the device. Here 0.7 modulation index is taken for the simulation.

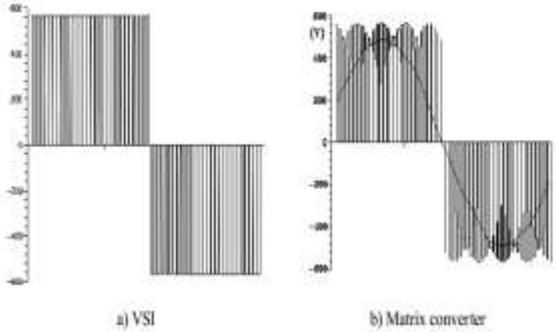


Figure14. Output voltage waveforms generated by a VSI and a matrix converter

Since no energy storage components are present between the input and output side of the matrix converter, the output voltages has to be generated directly from the input voltages. Each output voltage waveform is synthesized by sequential piecewise sampling of the input voltage waveforms. The sampling rate has to be set much higher than both input and output frequencies, and the duration of each sample is controlled in such a way that the average value of the output waveform within each sample period tracks the desired output waveform. As consequence of the input-output direct connection, at any instant, the output voltages have to fit within the enveloping curve of the input voltage system. Under this constraint, the maximum output voltage the matrix converter can generate without entering the over- modulation range is equal to 1.5times of the maximum input voltage: this is an intrinsic limit of matrix converter and it holds for any control law , The output voltage of a VSI can assume only two discrete fixed potential values, those of the positive and negative DC-bus. In the case of the matrix converter the output voltages can assume either input voltage a, b or c and their value is not time-invariant: the effect is a reduction of the switching harmonics.

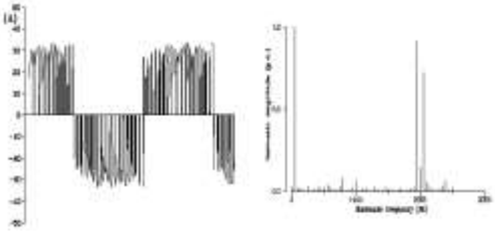


Figure15. matrix converter input current and harmonic distortion

The matrix converter performance in terms of input currents represent a significant improvement with respect to the input currents drawn by a traditional VSI converters with a diode bridge rectifier, whose harmonic spectrum shows a high content of low-order harmonics. By the light of the standards related to power quality and harmonic distortion of the power supply this is a very attractive feature of matrix converter,

In comparison with conventional PET with DC-link, in proposed converter power delivery stages and power electronic converters have been reduced and AC/AC matrix converter is used replaced by two converters (rectifier and inverter). This idea leads to the loss reduction, by processing the power in one stage instead of two stages.

Operation of proposed PET is described by Fig. 16. In this case the line voltage is 3.8 kV and the PET power is 30 kVA. Fig. 16(a) shows input line voltage of PET. As it can be seen in Fig. 16(b), the DC-link voltage of input stage is 7800 V. The voltage controller in Fig. 5 acts so that the DC-link voltage is regulated in reference value. Fig. 16(c) depicts the output voltage of VSC in isolation stage that transforms DC voltage to medium frequency AC voltage as the transformer primary voltage. The level of medium frequency AC voltage in secondary side is changed by MF transformer in Fig. 16(d). In the output stage, the medium frequency voltage is revealed as a 50 Hz waveform by AC/AC matrix converter. Fig. 16(e) shows load voltage between phase (a) and phase (b) before LC filter and load output voltage is shown in Fig. 16(f). Fig. 16(a) shows input line voltage of PET. As it can be seen in Fig. 16(b), the DC-link voltage of input stage is 7800 V. The voltage controller in Fig. 5 acts so that the DC-link voltage is regulated in reference value. Fig. 16(c) depicts the output voltage of VSC in isolation stage that transforms DC voltage to medium frequency AC voltage as the transformer primary voltage.

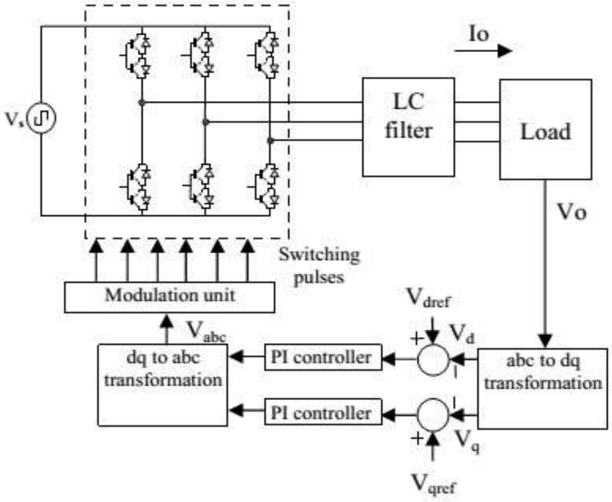


Figure17.Circuit control of output stage

Fig. 16(a) shows input line voltage of PET. As it can be seen in Fig. 16(b), the DC-link voltage of input stage is 7800 V. The voltage controller in Fig. 5 acts so that the DC-link voltage is regulated in reference value. Fig. 16(c) depicts the output voltage of VSC in isolation stage that transforms DC voltage to medium frequency AC voltage as the transformer primary voltage. The level of medium frequency AC voltage in secondary side is changed by MF transformer in Fig. 16(d). In the output stage, the medium frequency voltage is revealed as a 50 Hz waveform by AC/AC matrix converter. Fig. 16(e) shows load voltage between phase (a) and phase (b) before LC filter and load output voltage is shown in Fig. 16(f).

Fig. 10 shows the PET input power factor correction ability. In these simulations the active load is assumed to be 20 kW and the reactive power is assumed to be 10 kVAR inductive. Fig. 10(a) and Fig. 10(b) show phase voltages and currents of the load. Voltage and current for one phase together are shown in Fig.10(c). It is considered the power factor is 0.5 lag. Fig. 10(d) show input phase voltage and current. As it can be seen, power factor is 1 in the input when the load is lag

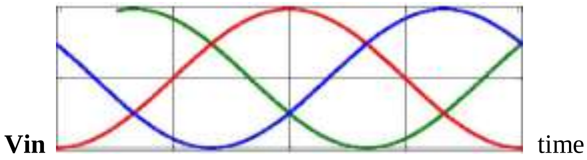


Figure 16a-Input Voltage

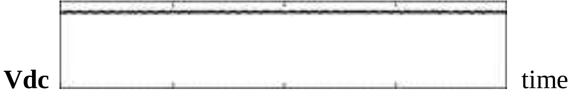


Figure 16b-DC link voltage

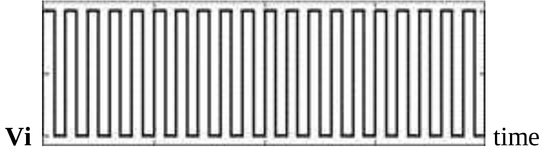


Figure 16c-MF transformer primary voltage

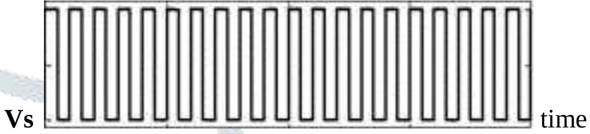


Figure 16d-MF transformer secondary voltage

Figure 16e-output voltage without filter

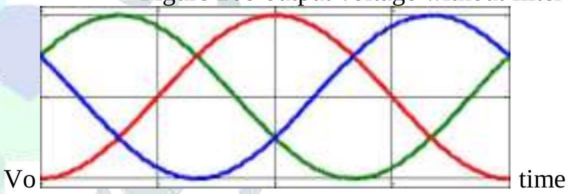


Figure 16f-output voltage

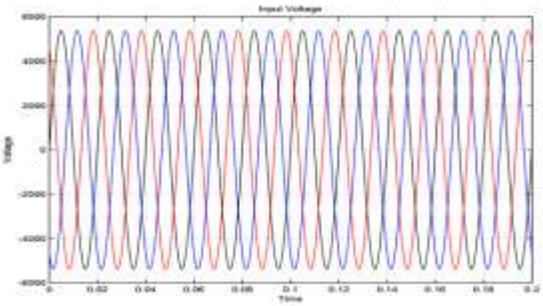
VI SIMULATION RESULTS

To evaluate the expected performance of the PET, the design was simulated to predict steady state performance. A prototype based on the proposed topology is simulated using MATLAB/SIMULINK.Also the parameters value used for simulations has been shown in Table I.Fig. 11 shows how the PET handles the voltage sag conditions. In Fig. 11(a), input voltage reduces 30 percent from t=0.4 s to t=0.5 s. As it can be seen, the PET acts properly and adjusts the output voltage to desired level (380 V) without any dip in output voltage.

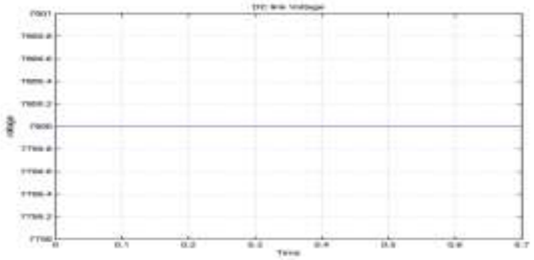
Parameters	Value
Input phase-phase voltage	3.8 kV
Power frequency	50 Hz
MF transformer	10:1, 1000 Hz,30 kVA
Output phase-phase voltage	380 V
Matrix converter switching frequency	2050 Hz
LC filter	2 mH, 220 µF
Load	20 kW+j10 kVAR
L, C_{dc}	3 mH, 2000 µF

TABLE I. PARMETERS OF

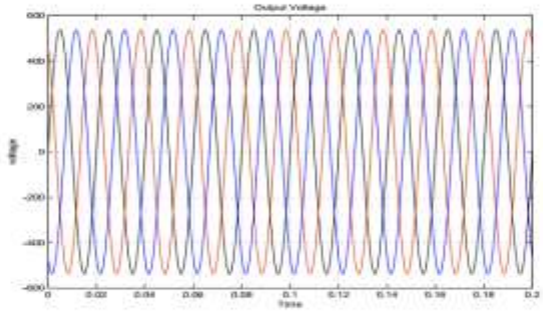
SIMULATION.
FOR RLC LOAD:



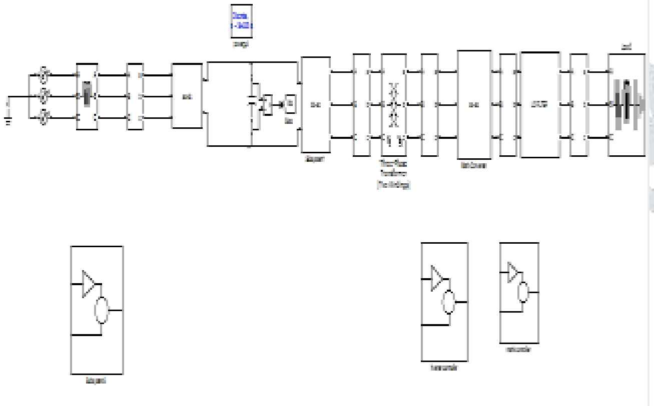
a)InputVoltage



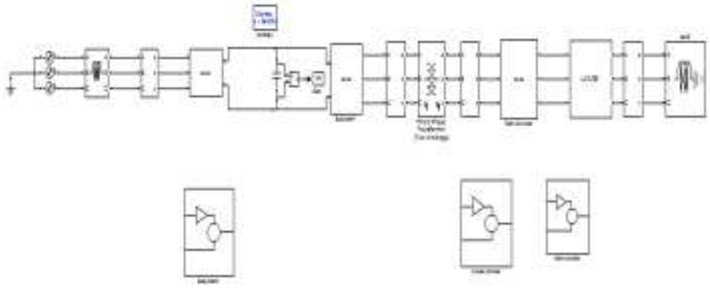
b)DC link Voltage



c) OutputVoltage



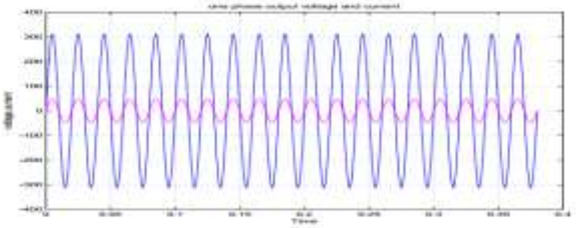
d) Simulink model for RLC load
Power electronic transformer current and voltage waveforms in inductive load



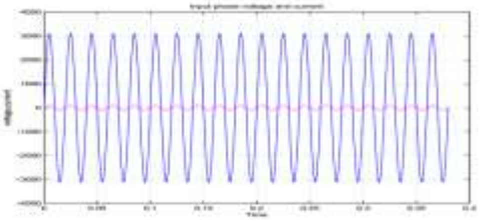
a)Simulink model for inductive load

b) Phase Output Voltage

c)Load Currents



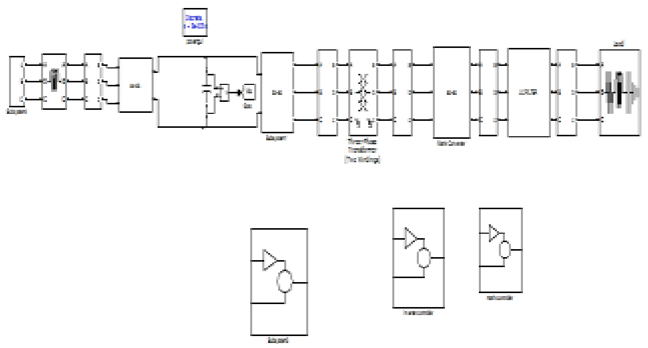
d

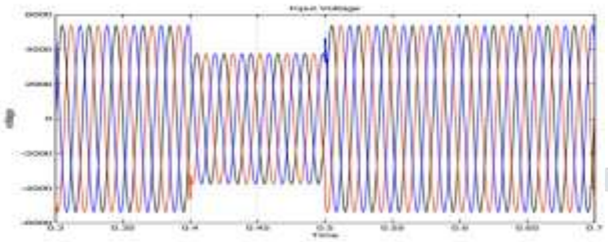


e

d&e)Single Phase Output and Input Current and Voltage waveforms

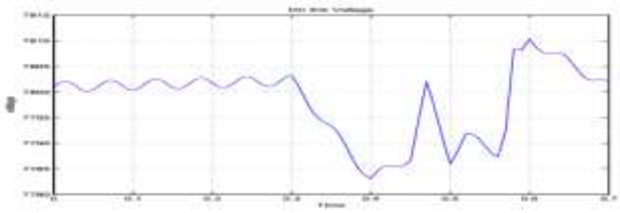
Simulation of PET with voltage sag condition



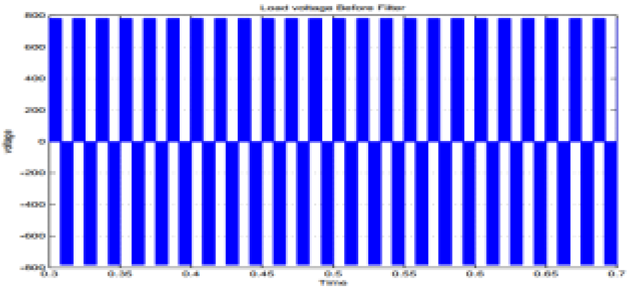


a) Input Voltage

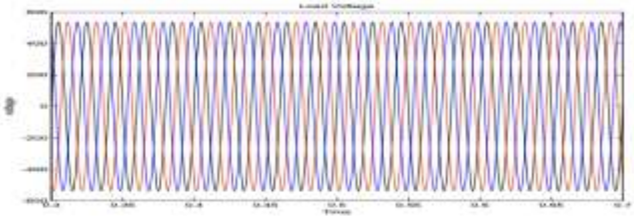
10A



b)DClinkvoltage

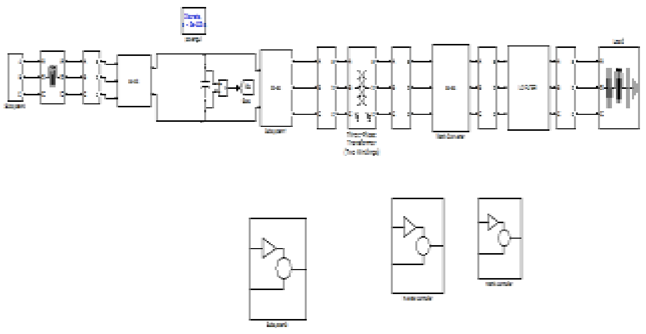


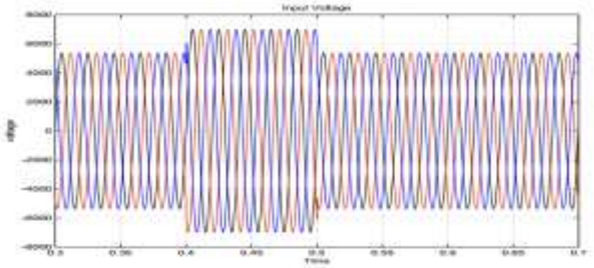
c) load voltage before filter



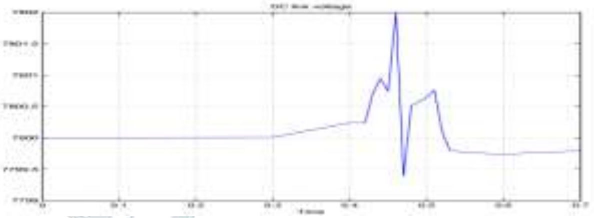
d) Load Voltage

Simulation model of PET for voltage sag condition

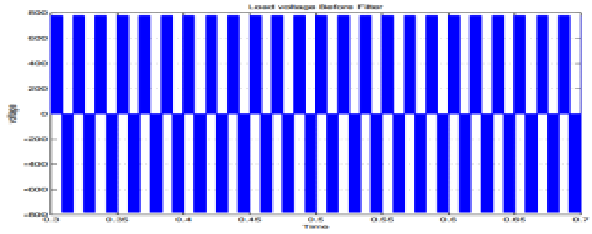




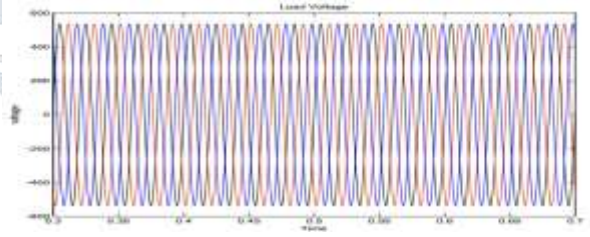
a) Input Voltage



b) DC link Voltage



c) Load Voltage Before Filter



d)Load Voltage

VI CONCLUSION AND FUTURE SCOPE

To reduce the voltage fluctuations and to maintain the power quality within limits power electronic transformer has been developed. This power electronic transformer consists of power electronic converters on both sides of the transformer. The proposed PET consist of AC/DC and DC/AC converter which consist of DC link capacitor. The control block consists of both Fuzzy logic controller and PI controller. Both these controllers will perform efficiently with reduced errors. The secondary of the PET consist of a Matrix converter which is an AC/AC converter which converts high switching frequency into supply frequency. If there are any disturbances such as voltage sag and voltage swell in supply side these disturbances are not carry forwarded to the load side. These disturbances are nullified using fuzzy and PI controllers.

The proposed Power electronic transformer is developed using MATLAB/SIMULINK model and voltage sag, voltage swell are introduced in the input side are simulated. According to the designed PET the voltage variations are reduced and required voltages have been supplied to load side without any disturbances even though there is disturbance in the supplied input voltages. The MATLAB/SIMULINK models and its respective results have been presented above. The variations considered are voltage sag, voltage swell, feeding a pure inductive load.

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